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Transient High Mass X-ray Binaries

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Abstract. High Mass X-ray Binaries (HMXBs) are interesting objects that provide a wide range of observational probes to the nature of the two stellar components, accretion process, stellar wind and orbital parameters of the systems. A large fraction of the transient HMXBs are found to be Be/X-ray binaries in which the companion Be star with its circumstellar disk governs the outburst. These outbursts are understood to be due to the sudden enhanced mass accretion to the neutron star and is likely to be associated with changes in the circumstellar disk of the companion. In the recent years, another class of transient HMXBs have been found which have supergiant companions and show shorter bursts. X-ray, infrared and optical observations of these objects provide vital information regarding these systems. Here we review some key observational properties of the transient HMXBs and also discuss some important recent developments from studies of this class of sources. The X-ray properties of these objects are discussed in some detail whereas the optical and infrared properties are briefly discussed.

Keywords : stars: binaries: general – stars: pulsars: general – stars: neutron – X-rays: binaries – X-rays: bursts – transients

1. Introduction

X-ray binaries are the brightest X-ray sources in the sky. In these systems, a compact object which is either a white dwarf, a neutron star or a black hole, and a normal star which is in the process of evolution, revolve around the common centre of mass. Depending on the mass of the binary companion, these systems are classified into two types such as (a) Low Mass X-ray Binaries (LMXBs; mass of the companion ≤ 3 $M_\odot$) and (b) High Mass X-ray Binaries (HMXBs; mass of

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the companion ≥ 10 $M_{\odot}$). The HMXBs contain massive and early-type (O or B-type) companion stars where as in case of LMXBs, the spectral type of the binary companion is A-type or later. It is seen that the HMXBs are generally concentrated towards the Galactic plane in contrast to the LMXBs which are found near the Galactic centre, Galactic bulge, in the Galactic plane, and also in the globular clusters in the halo. Mass-accretion takes place from the binary companion to the compact object through Roche-lobe overflow (in case of LMXBs) or/and capture of stellar wind of the companion (in case of HMXBs). As the binary companion evolves and fills the Roche-lobe, mass transfer takes place from the companion star to the compact object through the inner Lagrange point. In case of most HMXBs, however, the dominant process of mass accretion from the companion to the compact object is by the capture of the stellar wind of the companion. The accreted mass then spirals around the compact object forming a disk like structure, known as an accretion disk, before falling on to the compact object. The gravitational pull of the neutron star or black hole in the binary system accelerates the matter to extremely high velocities. The accelerated matter approaches the compact star, and if it has a stellar surface, most of the kinetic energy of the accreted material is converted to thermal energy which is radiated away primarily in the X-ray energy band. In some cases, especially if the compact star does not have a strong magnetic field, there can also be a outflow in the form of a collimated jet from the compact star or a disk wind.

The HMXB systems are strong X-ray emitters by the process of accretion of matter from the OB companion. Based on the type of the companion star, these systems are further classified into Be/X-ray binaries and supergiant X-ray binaries. The Be/X-ray binaries represent the largest subclass of high mass X-ray binaries. About 2/3 of the identified systems fall into this category. In these systems, the optical counterpart of the neutron star is either a dwarf, subgiant or a giant OB star (luminosity class of III, IV or V) which shows spectral lines in emission. The mass donor in the Be binary systems is generally a B star that is still on the main sequence and lying well inside the Roche surface. In these Be binary systems, the compact object (almost always a neutron star) is typically in a wide orbit with moderate eccentricity with orbital period in the range of 16–400 days. Evolutionary calculations show that Be star and white dwarf or Be star and black hole should also be common types of systems. However, no clear evidence of existence of such systems has been shown as yet (Zhang, Li & Wang 2004 and references therein). Mass transfer from the Be companion to the neutron star takes place through the equatorial circumstellar disc thought to be formed from the matter expelled from the rapidly rotating Be star. The neutron star in these systems spends most of the time far away from the circumstellar disc surrounding the Be companion. The X-ray spectra of these Be/X-ray binaries are usually hard. The hard X-ray spectrum along with the transient nature are important characteristics of the Be/X-ray binaries.

In case of supergiant X-ray binaries, the optical counterpart is a star of luminosity class of I or II. In these systems, the compact object orbits around the supergiant early-type star which is deep inside the highly supersonic wind. The optical companion emits a substantial stellar wind with a mass loss rate of 10^{-6}–10^{-8} $M_{\odot}$ yr^{-1} with a terminal velocity up to 2000 km s^{-1}. The supergiant X-ray binaries are further subdivided into two groups according to the dominant mode of mass transfer: (a) capture of the stellar wind of the optical companion and (b) Roche lobe overflow. In some of these systems, both types of mass transfer may be taking place (Blondin,

Stevens & Kallman 1991). Although capture from a high-velocity stellar wind is inefficient, the large mass-loss rate in the wind can result in an appreciable mass accretion rate onto the neutron star that is sufficient to emit radiation in X-ray band. Vela X-1 is the well known wind-fed supergiant X-ray binary pulsar. In case of Roche lobe overflow, the mass donor fills its Roche lobe and results in transfer of material from the companion to the neutron star through the first Lagrange point and forms an accretion disk around the neutron star. This is a very efficient form of accretion and results in a mass transfer rate much larger than by capture of the wind alone. The X-ray photons emitted from the compact object through either of the accretion processes, must propagate through the stellar wind to the observer, which causes absorption, scattering and reprocessing of the X-ray spectrum. Some of the supergiant X-ray binaries in which the Roche lobe overflow is the dominant mode of mass accretion, are usually persistent X-ray sources. SMC X-1, LMC X-4 and Cen X-3 are amongst the best candidates for the disk-fed (via Roche lobe overflow) supergiant X-ray binary pulsars.

Most of the high mass X-ray binaries are transient sources that are usually quiescent and occasionally become X-ray bright for a duration of a few days to several tens or hundreds of days. During the peak of the outburst, some of these sources are among the brightest X-ray sources in the sky. During the X-ray outbursts, the X-ray brightness/luminosity of some of the transient sources increases by up to four to five orders of magnitudes. The huge range of luminosity change makes these objects interesting to study in X-ray bands. While the X-ray bursts, outbursts, flares are generally transient and unpredictable, the Be/X-ray transients often show regular and periodic outbursts on time scales in the range of tens of days to several hundreds of days, same as their orbital periods.

The Be/X-ray binaries display two types of X-ray outbursts such as Type I and Type II outbursts. Type I outbursts are short and periodic outbursts of moderate luminosity ($L_{\rm X} \leq 10^{35}$–10^{37} erg s^{-1}) which occur close to the time of periastron passage of the neutron star in the wide eccentric orbit. This suggests an enhanced accretion caused by the proximity of the neutron star to the Be star companion at periastron. These outbursts last for a few days to tens of days and are different from the Type II outbursts which are caused by enhanced episodic outflow of the Be Star. Type II outbursts, are infrequent giant outbursts with peak luminosities reaching as high as $L_{\rm X} = 10^{38}$ erg s^{-1} or more. These outbursts last for several weeks to months. The timing of these outbursts is not related to any underlying orbital period of the system. These Type II outbursts occur when a large fraction of the Be star's disk is believed to be accreted. The Type I outbursts, though they occur only around the time of the periastron passages, do not occur in all the binary orbits and often a series of Type I outbursts are seen following a large Type II outburst. Fig. 1 shows the presence of Type I and Type II X-ray outbursts in the *Swift*/BAT light curves (in 15–50 keV energy range) of A0535+262 and EXO 2030+375 Be/X-ray binary systems.

Supergiant Fast X-ray Transients (SFXTs) is a new class of high mass X-ray binaries, discovered with *Integral* observations (Sguera et al. 2005), that are associated with OB supergiant stars. These objects are characterized by the occurrence of very fast X-ray outbursts. Outside the outbursts, they are not detected as X-ray sources or only detected as a weak source. In quiescence, the X-ray luminosity of these objects is found to be $\sim 10^{32}$ erg s^{-1} (Bozzo et al. 2010),

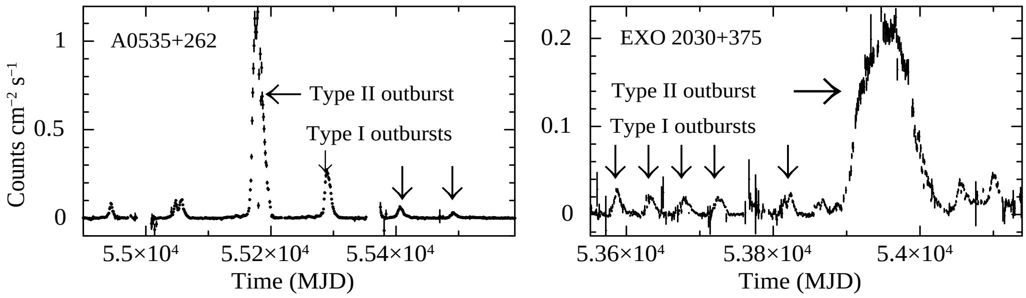

Figure 1. The outburst profiles of Be/X-ray binaries A0535+262 (left panel) and EXO 2030+375 (right panel) are shown in 15–50 keV energy band, as seen by *Swift*/BAT. Type I and Type II X-ray outbursts seen in these systems are marked in both panels.

with a dynamic range of 3–5 orders of magnitude for the outbursts. The X-ray outbursts in these systems are characterized by bright flares with a duration of a few hours (lasting from $\sim$ 3 to $\sim$ 8 hours, rarely even a few days), very sharp rise, reaching the peak of the flare in $\leq$ 1 h. Since the SFXTs are very bright in X-ray band but for very short duration (during the short transient outburst), these objects are difficult to detect with the X-ray sky monitors. During the outburst, the X-ray spectra of these sources are found to be hard and similar to that of other HMXBs hosting accreting neutron stars. Even though pulse periods have only been measured for a few SFXTs e.g. IGR J11215−5952 ($\sim$ 187 s; Swank et al. 2007) and IGR J18410−0535 ($\sim$ 4.7 s; Sidoli et al. 2008), it is likely that all SFXTs might host a neutron star. The mechanism producing these short outbursts is still being debated. It is probably related to either the properties of the wind from the supergiant companion (Negueruela et al. 2008 and references therein) or to the presence of a centrifugal or magnetic barrier (Grebenev & Sunyaev 2007; Bozzo, Falanga & Stella 2008).

Here we discuss various important temporal, spectral, and joint temporal-spectral properties of HMXBs in which there have been significant recent developments. Then we discuss some other emerging important issues of HMXBs, like the SFXT phenomena. We also briefly discuss the optical/IR properties of the transient HMXBs during the outbursts and mention the potential of the upcoming mission Astrosat in furthering investigations of this important class of sources.

2. Aspects of transient HMXBs probed during the outbursts

The transient HMXBs show change of X-ray intensity by several orders of magnitudes during the outbursts, most likely due to changes in the mass accretion rate. This allows probe of several features like the pulse shape, accretion torque, quasi-periodic oscillations, energy spectrum, cyclotron absorption features in the spectrum over a large range of X-ray luminosity. Changes in the mass accretion rate is expected to cause changes in the accretion process in a complex way, for example by changes in the inner disk radius, accretion torque, height of the accretion column, X-ray beaming pattern, and even temperature of the electrons that produce the hard X-rays by Compton up-scattering. In the last few years, availability of several medium and hard X-ray

transient monitors, several narrow field X-ray instruments with excellent timing and spectral capabilities and wide energy coverage, and intense observation programs have enabled very detailed investigations of transient HMXBs. Some of the important aspects are discussed below.

2.1 Temporal properties

Observations with the Proportional Counter Array (PCA) instrument of the Rossi X-ray Timing Explorer (*RXTE*) has been most important in investigation of the temporal studies of all kinds of X-ray sources, including the transient HMXBs. In addition, the Gamma-ray Burst Monitor (GBM) instrument onboard Fermi has also been a major contributor in studies of pulsar spin-up and QPOs. The temporal characteristics of the SFXTs have primarily been revealed from *Swift* and *Integral* observations.

2.1.1 *Luminosity dependence of pulse profiles*

Accretion-powered X-ray pulsars, both transient and persistent sources, are known to show luminosity dependence of the pulse profile. Differences in shape of X-ray pulse profiles are considered to be due to the differences in the geometrical configuration of the accretion column around the magnetic axis (Nagase 1989). The structure of the accretion column near the magnetic poles of the neutron star determines the basic profile of the pulse pattern. A most remarkable example of pulse profile evolution was investigated in EXO 2030+375 (Parmar, White & Stella 1989). The evolution of the pulse profile during the outbursts indicates changes in the accretion flow from the inner accretion disc to the neutron star. Along with the luminosity dependence, most of the accretion-powered pulsars also show strong energy dependence of the pulse profile, discussed in Section 4.

Luminosity dependence of pulse profiles are seen in several transient HMXB pulsars. In one of the nearby and brightest Be/X-ray binary pulsar A0535+262, the pulse profile is known to be single peaked during the quiescent phase (Mukherjee & Paul 2005) whereas it is double-peaked and complex during the X-ray outbursts (Naik et al. 2008; Caballero et al. 2007). An extensive study of the pulse profiles of the recent outbursts of two transient pulsars GX 304−1 and 1A 1118−61 showed significant evolution during the outburst (Devasia et al. 2011a, 2011b; Maitra, Paul & Naik 2011). Apart from the energy and luminosity dependence of pulse profiles, dips or dip-like features in the pulse profiles are also seen in many transient X-ray pulsars. The presence of dips/dip-like structures in the pulse profiles of these X-ray pulsars is described as due to the obscuration of X-ray radiation from the region near the magnetic poles by dense matter in the accretion streams along which the matter flows from the inner accretion disk to the neutron star. The associated spectral signatures of this are discussed in Section 4.

2.1.2 *Accretion torque*

In accretion powered binary X-ray pulsars, the flow of material from the companion star to the neutron star is interrupted when the magnetic stress starts dominating over the material stresses at the magnetospheric radius $r_{\rm m}$. Matter becomes attached to the magnetic field lines at $r_{\rm m}$ and gets transported to the magnetic poles of the neutron star. The torque of the infalling material captured from the accretion disk and the torque transferred by the accretion disk to the neutron star through the magnetic field lines cause changes in the neutron star spin-rate. At high mass accretion rate, during the outbursts, the neutron stars experience an accretion torque which leads to spinning up of the neutron star. At low accretion rate, like during the quiescent period between the outbursts, the neutron stars often experience net negative torque (Bildsten et al. 1997). At very low accretion rates, if the magnetospheric radius lies outside the corotation radius $r_{\rm co}$, where the Keplerian orbital frequency equals the spin frequency of the neutron star, matter may be expelled from the system. In such cases, accretion can be centrifugally inhibited which is called "propeller effect". During this regime, the neutron star spins down rapidly and pulsations may not even be detectable. In several cases, disappearance of pulses at low flux rate have been shown as evidence of the propeller effect (Cui 1997 and references therein). However, there are also counter examples (Mukherjee & Paul 2005; Naik, Paul & Callanan 2005). Due to this complex nature of the relation between the mass accretion and net torque onto the neutron star, the transient sources are very good candidates to study the interaction between material in the accretion disk and the magnetic field through measurements of rate of change of spin period and X-ray luminosity.

The accretion torque theory predicts that the magnetospheric radius should decrease with increase in the rate of mass accretion as per the relation $r_{\rm m} \propto \dot{M}^{-2/7}$ for $r_{\rm m} < r_{\rm co}$ (Ghosh & Lamb 1979). This implies that a neutron star spins up with a rate related to the mass accretion rate as $\dot{\nu} \propto \dot{M}^{-6/7}$. Such a dependence was tested in several transient X-ray pulsars. A correlation between the spin-up rate and X-ray luminosity has been observed during outburst of several transient binary X-ray pulsars such as EXO 2030+375 (Reynolds et al. 1996, Parmar et al. 1989), 2S 1417−62 (Finger, Wilson & Chakrabarty 1996), A 0535+262 (Bildstein et al. 1997), GS 0834−43 (Wilson et al. 1997), GRO J1744−28, (a LMXB pulsar; Bildsten et al. 1997). Very recently, the long-term spin frequency evolution history of A0535+262 (since 1975 to 2006) was analyzed in detail. It was found that this Be/X-ray pulsar shows a global spin-up trend in which short, rapid spin-up episodes during the outbursts are followed by extended, slow spin-down during the quiescent periods (Camero-Arranz et al. 2011). From the long term spin frequency evolution study of this pulsar with the *Fermi/GBM* a strong correlation was found between the pulse flux and the spin-up rate which is in agreement with the earlier findings in A0535+262 and other transient pulsars.

2.1.3 *Quasi-periodic oscillations and its relation with X-ray luminosity*

Quasi-periodic oscillations (QPOs) in X-ray binary pulsars are thought to be related to the motion of inhomogeneously distributed matter (blobs) in the inner accretion disk, and they provide useful

information about the interaction between accretion disk and the neutron star. In X-ray pulsars, the QPO frequency ranges from $\sim$ 1 mHz to $\sim$ 40 Hz, and they can be from $\sim$ 100 times smaller to $\sim$ 100 times larger than the pulsar spin frequencies (Psaltis 2006). The presence of QPOs in the power density spectrum of X-ray pulsars is generally explained with the Keplerian frequency model (van der Klis et al. 1987) or the magnetospheric beat frequency model (Alpar & Shaham 1985). In Keplerian frequency model, the QPOs arise from the modulation of the X-rays by inhomogenities in the accretion disc, at the Keplerian frequency. In this model, the QPO frequency is same as that of the Keplerian frequency of the inner accretion disk. When the Keplerian frequency at the inner edge of the accretion disk is below the neutron star spin frequency, centrifugal forces are expected to inhibit accretion. Keplerian frequency model, therefore, can be applicable only when the QPO frequency is above the neutron star spin frequency, as seen in EXO 2030+375 (Angelini, Stella & Parmar 1989), A0535+262 (Finger et al. 1996). In the beat frequency model, blobs of matter orbits the neutron star approximately at the Keplerian frequency of the inner edge of the accretion disk, accreting at a rate that is modulated by the rotating magnetic field. This produces power spectral feature at the beat frequency between Keplerian frequency and spin frequency of the neutron star. According to this model, the QPO frequency is equal to the difference between the Keplerian frequency of the inner accretion disk and the spin frequency of the pulsar.

In accretion powered X-ray pulsars, QPOs seem to occur more in transient sources compared to the persistent ones. Transient HMXB pulsars from which QPOs have been detected are KS 1947+300 (20 mHz; James et al. 2010), SAX J2103.5+4545 (44 mHz; Inam et al. 2004), A0535+262 (50 mHz; Finger et al. 1996), V0332+53 (51 mHz; Takeshima et al. 1994), and 4U 0115+63 (62 mHz; Soong & Swank 1989), XTE J1858+034 (110 mHz; Paul & Rao 1998; Mukherjee et al. 2006), EXO 2030+375 (200 mHz; Angelini et al. 1989), XTE J0111.2−7317 (1270 mHz; Kaur et al. 2007), 4U 1901+03 (James et al. 2011), 1A 1118−61 (Devasia et al. 2011a), MAXI J1409−619 (Kaur et al. 2010) and GX 301-4 (Devasia et al. 2011b). The power density spectra of four sources are shown in Fig. 2, in which the QPO features are clearly seen. In two of the sources the QPO frequency is higher than the spin frequency and it is opposite for the remaining two sources. It has been found that the QPOs are rare and transient events in HMXB pulsars. In transient HMXB pulsars which show QPOs, the feature is not detected always during all the observed X-ray outbursts. In some sources (e.g. A0535+262), the QPO feature is present all along in some of the outbursts while completely absent in some other outbursts (Finger et al. 1996; Camero-Arranz et al. 2011). While in some other sources (4U 1901+03 and 1A 1118−61), the QPOs are detected only near the end of the outburst, when the X-ray intensity has decreased to a small fraction of the peak intensity. At high mass-accretion rate (during X-ray outbursts), the accretion disc is expected to extend closer to the neutron star. A positive correlation between the QPO centroid frequency and the X-ray intensity is, therefore, expected in the transient HMXB pulsars (Finger 1998). A strong correlation between the QPO centroid frequency with the X-ray intensity and neutron star spin-up rate was seen in the transient Be/X-ray binary pulsar A0535+262 (Finger et al. 1996; Camero-Arranz et al. 2011). Similar correlation between the QPO frequency and the source intensity was found in case of the transient HMXB pulsar EXO 2030+375 (Angelini et al. 1989). In case of XTE J1858+034, though the correlation between QPO frequency and the X-ray flux was not clearly seen, the QPO frequency and the one day averaged X-ray flux decreased with time during the April–May 2004 X-ray outburst

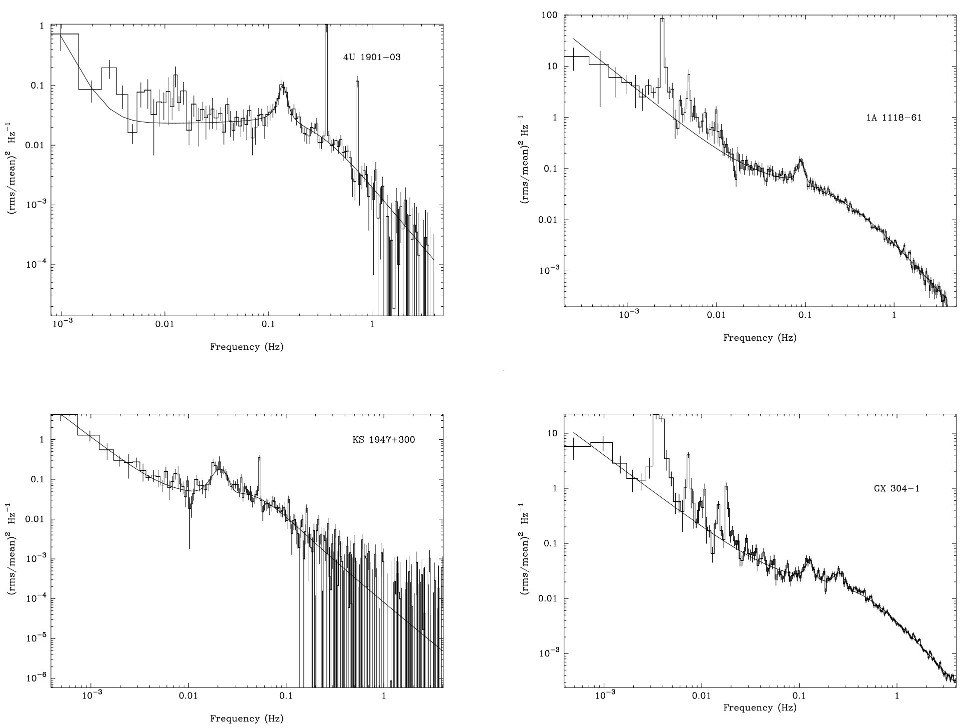

Figure 2. The quasi periodic oscillations discovered recently in four transient accretion powered X-ray pulsars are shown here. (Top: 4U 1901+03 and 1A 1118−61; bottom: KS 1947+300 and GX 304−1). The pulse frequency peaks and its harmonics are also seen along with the broad QPO features.

(Mukherjee et al. 2006; Paul & Rao 1998). This suggests that the observed QPO frequency, like the spin-up rate and X-ray flux, is controlled by the mass accretion rate.

2.1.4 *Orbital parameters, orbital evolution*

In the X-ray binaries with eccentric orbits, tidal interactions may result in circularisation and apsidal motion (Lecar, Wheeler & McKee 1976) that can be measured if the compact object is an X-ray pulsar. Apsidal motion is the rate of change of the longitude of periastron of the binary orbit. The rate of apsidal motion is directly related to the distribution of mass in the tidally distorted companion star and hence is directly related to the stellar structure constant of the companion star. The transient Be X-ray binaries, which often have accretion powered X-ray pulsars are suitable candidates to measure the orbital parameters and measurements carried out during multiple outbursts over several years can be used to estimate the apsidal motion constant. In addition to the tidal effect, the orbits of the X-ray binary systems evolve due to mass transfer

from the companion star to the compact object, mass loss from the binary system in the form of stellar wind from the companion star, and/or gravitational wave radiation (Verbunt 1993). In the case of HMXB systems which often have orbital period between a few days to a few hundred days, however, the effect of gravitational wave radiation and even that of mass transfer is weak compared to the other processes. The best way to measure orbital evolution of X-ray binaries is by repeated measurements of orbital parameters by pulse timing. However, measurement of orbital parameters of the transient HMXBs by pulse timing requires long X-ray observations during the outbursts. The complete set of orbital parameters is known only in 18 Be/X-ray binary systems out of a total of ~130 sources in the catalogue of Be/X-ray binaries in our Galaxy, the Large Magellanic Cloud (LMC) and the Small Magellanic Cloud (SMC) (Raguzova & Popov 2005).

Using observations made with the *RXTE*-PCA, the complete set of orbital parameters have recently been measured for the transient Be/X-ray binary pulsars V0332+53 and 2S 1417−624 along with a successful measurement of the rate of apsidal motion in 4U 0115+63 (Raichur & Paul 2010). For the HMXB pulsar 4U 0115+63, the *RXTE* observations of the X-ray outbursts in 1999 and 2004 were used to determine the changing orbital parameters, and along with the previous measurements the rate of apsidal motion was determined to be ($\dot{\omega} = 0^{\circ}.04 \pm 0^{\circ}.02$ yr^{-1}). Orbital parameters of several other HMXB transients have been measured accurately in the Milky Way. Similar measurements are also being done in case Be/X-ray binaries in the Small Magellanic Could (SMC) using data from the *RXTE* observatory. The Be/X-ray binary systems in the low-metallicity environment in the SMC show similar behaviour in the distribution of orbital periods and eccentricities as that of the HMXBs in our Galaxy. This suggests that metallicity may not play an important role in the evolution of such systems (Townsend et al. 2011).

2.1.5 *Power Density Spectra of HMXBs*

Most of the accretion powered X-ray pulsars, in addition to their periodic modulations, show *aperiodic* X-ray variabilities in a wide range of time scales. These variabilities in the X-ray intensity are reflected as various different types of features in the Power Density Spectra (PDS). Aperiodic variability is more common than periodic variability in X-ray binary systems as the accretion flow from the companion to compact object is generally turbulent. Characterizing the aperiodic variabilities of X-ray sources is an important step in understanding the complicated dynamics of the accretion disk around the compact objects. The PDS of accreting X-ray pulsars where the accretion disk at the magnetospheric boundary could be close to being in corotation with the neutron star, have a distinct break/cut-off around the neutron star spin frequency (Hoshino & Takeshima 1993). In these systems, the break in the PDS probably represents the transition from the disk-like accretion flow to magnetospheric flow at the frequency characteristic of the magnetospheric radius.

3. X-ray spectrum and spectral evolution during the outburst

It has already been discussed above that the majority of the HMXBs are known to be Be/X-ray binaries. Mass transfer from the Be companion to the neutron star takes place through the circumstellar disk. Strong X-ray outbursts are normally seen when the neutron star passes through the circumstellar disk, often during the periastron passage. Transient X-ray pulsars in general are prone to wide variations in mass accretion rates and are suitable systems to test the various accretion regimes onto high magnetic field neutron stars. The X-ray luminosity of these transient X-ray pulsars is highly variable i.e. from $10^{32} - 10^{33}$ erg s^{-1} during quiescence to $10^{36} - 10^{37}$ erg s^{-1} during the peak of the outbursts. Though the mass accretion onto neutron stars in binary systems is a complex physical process, broad band X-ray spectra of the X-ray pulsars can be described by relatively simple models. A considerable fraction of the photons emitted from the neutron star gets reprocessed by the matter along the line of sight, accretion column, accretion disk before reaching the observer. Around the periastron passage, there is possibility of an increase in the column density of matter along the line of sight. Close to the neutron star, the accreting matter is phase locked in the strong magnetic field and these accretion streams can also cause absorption and reprocessing of the X-rays.

The spectra of the binary X-ray pulsars are generally described by a power-law, broken power-law or power-law with high energy cutoff continuum models. In some cases, the pulsar spectrum has also been described by the Negative and Positive power-law with EXponential cutoff (NPEX) continuum model which is an approximation of the unsaturated thermal Comptonization in hot plasma (Makishima et al. 1999). This continuum model reduces to a simple power-law with negative slope at low energies that is used to describe the spectra of accretion powered X-ray pulsars at low energies. The analytical form of the NPEX model is

$$NPEX(E) = (N_1 E^{-\alpha_1} + N_2 E^{+\alpha_2}) \exp\left(-\frac{E}{kT}\right)$$

where E is the X-ray energy (in keV), N_1 and α_1 are the normalization and photon index of the negative power-law respectively, N_2 and α_2 are those of the positive power-law, and kT is the cutoff energy in units of keV. The first power-law is the usual high energy component produced by inverse Compton scattering of the soft X-ray photons and the second power-law describes the black body radiation, if the corresponding photon index α_2 is close to 2. The physical motivation for this model is the coupling between the accretion hot spot and the up-scattered X-ray photons in the accretion column, which results in a cutoff power-law.

In case of a few X-ray pulsars, it has been reported that the absorption has two different components (Endo, Nagase & Mihara 2000; Mukherjee & Paul 2004). In this model, one absorption component absorbs the entire spectrum whereas the other component absorbs the spectrum partially. This model is known as partial absorption model. The partial covering model can also be described as consisting of two power-law continua with a common photon index but with different absorbing hydrogen column densities. The partial covering absorption model is applicable if the second absorbing component is smaller in size compared to the emission region. The analytical

form of the partially covering high energy cutoff power-law model is

$$N(E) = e^{-\sigma(E)N_{\rm H1}} \left(S_1 + S_2 e^{-\sigma(E)N_{\rm H2}}\right) E^{-\Gamma} I(E)$$

where

$$I(E) = \begin{cases} 1 & \text{for } E < E_{\rm c}, \\ e^{-\left(\frac{E-E_{\rm c}}{E_{\rm f}}\right)} & \text{for } E > E_{\rm c}, \end{cases}$$

$N(E)$ is the measured spectrum, Γ is the photon index, $N_{\rm H1}$ and $N_{\rm H2}$ are the two equivalent hydrogen column densities, σ is the photo-electric cross-section, S_1 and S_2 are the normalizations of the two power law components, $E_{\rm c}$ is the cut-off energy and $E_{\rm f}$ the e-folding energy. According to this model, a part of the continuum source is obscured, resulting in a harder spectrum. If the absorbing component is in the form of an accretion stream or is a part of the accretion column, it can be phase locked with the neutron star, resulting into a phase-dependent column density and covering fraction. At higher energy, however, the partial covering absorption model is the same as a simple power-law model. Some results from pulse phase resolved spectroscopy of transient pulsars is further discussed in Section 4. A narrow iron fluorescence line at 6.4 keV is often found in the spectrum of HMXB pulsars.

Broad-band spectrum of the Be/X-ray binary pulsar GRO J1008−57 was found to be well fitted with all three continuum models as described above. The count rate spectra of GRO J1008−57 are shown in Fig. 3 along with the model components (top panels) and residuals to the best-fitting model (bottom panels). In case of the hard X-ray transient pulsar 1A 1118−61, 3–30 keV energy spectra obtained from several *RXTE* observations during an X-ray outburst in 2009 were found to be well described with a partial covering power-law model with a high-energy cut-off and an iron fluorescence line emission (Devasia et al. 2011a). Broad-band spectroscopy of *Suzaku* observations of the pulsar also revealed that the partial covering power-law model is the suitable model to describe the spectra (Maitra et al. 2011). The spectrum of transient HMXB pulsar GX 304−1 was found to be better described by the partial covering power law with high energy cut-off model than the power law with high energy cut-off model (Devasia et al. 2011b). The partial covering absorption model is found to be most suitable continuum model even in case of persistent HMXB pulsars such as GX 301−2 (Mukherjee & Paul 2004) and Cen X-3 (Naik, Paul & Ali 2011).

In order to investigate the spectral evolution of the transient HMXB pulsars during outbursts, frequent X-ray observations of the pulsar are required. Spectral evolution during the outbursts has been detected in several transient sources, in the simple form of change in hardness ratio (Reig 2008). Detailed study of spectral evolution during the outbursts have recently been carried for a few sources. Extensive *RXTE* observations of the transient HMXB pulsar GX 304-1 during an outburst in 2010 August was reported by Devasia et al. (2011b). They found that the 3–30 keV spectrum was well fitted with a partial covering power law model with a high energy cut-off and iron fluorescent line emission. Significant spectral evolution was seen during the outburst. The ratio of the spectra during the entire outburst to the spectrum on one epoch (close to the peak of the outburst; as shown in Fig. 4), showed the softening of the spectrum below $\sim$ 18 keV and hardening beyond $\sim$ 18 keV, during the decay of the outburst. Similar spectral evolution

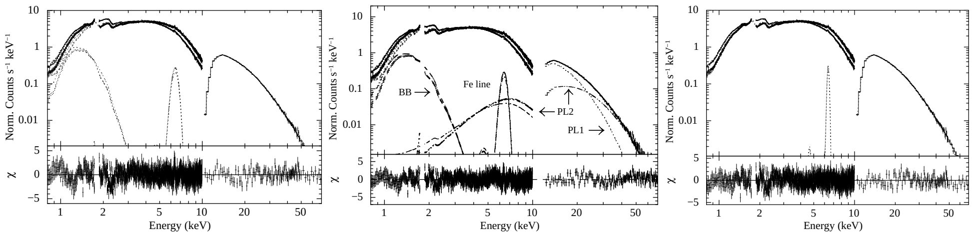

Figure 3. Energy spectrum of GRO J1008−57 obtained with the XIS and PIN detectors of *Suzaku* observation, along with the best-fitting models comprising (a) a blackbody component, high energy cut-off power-law continuum model and a narrow iron line emission (left panel), (b) a blackbody (BB) component, NPEX continuum model and a narrow iron (Fe line) emission (middle panel), and (c) a partially absorbed high energy cut-off power-law continuum model and a narrow iron line emission (right panel). The bottom panels show the contributions of the residuals to the χ^2 for each energy bin for the best-fitting models.

during the transient outbursts in HMXB pulsars has also been studied in 1A 1118−61 (Devasia et al. 2011a). The spectral changes indicate corresponding changes in the emission region with variations in the mass accretion rate.

3.1 Cyclotron lines in transient HMXB pulsars

X-ray binary pulsars are known to have very strong surface magnetic fields in the range of 10^{12}–10^{13} Gauss. The surface magnetic field strengths can be most accurately determined by measuring quantized electron cyclotron resonance features corresponding to transition between adjacent Landau levels, which are separated by $E_{a1} = 11.6 \times B_{12}(1+z)^{-1}$ (keV), where B_{12} is the magnetic field strength in the unit of 10^{12} Gauss and z is the gravitational redshift. In case of pulsars with magnetic field strength B_{12} in the range of 1 to 10, E_{a1} falls in the hard X-ray energy (10–100 keV) range. Therefore, detection of spectral absorption features at this resonance, called Cyclotron Resonant Scattering Feature (CRSF) is a powerful tool to accurately determine the pulsar magnetic fields. Using this spectral feature, the surface magnetic fields of about 15 binary pulsars have been accurately measured with several X-ray observatories such as *BeppoSAX*, *RXTE*, *Suzaku* and *Integral*. (Coburn et al. 2002 and references therein). The energy spectrum of Be/X-ray binary pulsar A0535+262 showing the presence of CRSF along with other model components is shown in Fig. 5.

Most of these pulsars are in transient HMXB systems. Another very interesting phenomenon in accreting X-ray pulsars is that several pulsars show luminosity dependent changes in the cyclotron resonance energy. Some are 4U 0115+63, A0535+262, X0331+53, Her X-1 (Nakajima et al. 2006; Terada et al. 2006; Nakajima, Mihara & Makishima 2010 and references therein). In the case of transient pulsars 4U0115+63 and X0331+53 (V0332+53), the cyclotron resonance energy has been found to correlate negatively with the source luminosity. The anti correlation between the X-ray luminosity and the cyclotron resonance energy is understood as a result of a decrease in the accretion column height, in response to a decrease in the mass accretion rate.

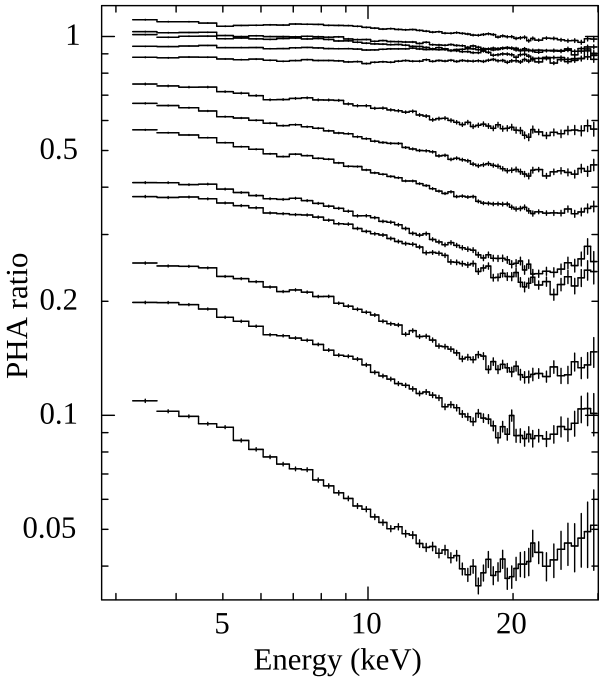

Figure 4. Ratios of the 3–30 keV X-ray spectrum obtained on different days of RXTE observations of GX 304-1 during its 2010 August outburst with the spectrum obtained on August 15 near the peak of the outburst are shown. A softening of the spectrum below about 18 keV and a hardening above 18 keV is evident during the decay of the outburst. The figure is taken from Devasia et al. (2011b).

Higher the luminosity, lower in energy is the CRSF produced. This is because, higher luminosity implies higher accretion rate and a larger height of the accretion column. The CRSF feature is thus produced further away from the surface of the neutron star (Nakajima et al. 2006) where the local dipole magnetic field is smaller. However, the anti-correlation is not seen in all the sources and the reason for this is not yet very clear.

4. Time resolved spectroscopy and energy resolved timing

Several of the X-ray observatories provide very good coverage in observation of the transient sources during their outbursts, either due to very flexible planning and maneuvering (*RXTE*-PCA, *Swift*-XRT) or due to the wide angle coverage (*Integral*-IBIS, *Swift*-BAT). This has enabled detailed studies of the timing and spectral properties over the long outburst periods of the HMXB transients. The large photon collection area of the *RXTE* and *Suzaku* also allow detailed pulse phase resolved spectroscopy or energy resolved pulse profile studies and some important results obtained in the recent years are briefly discussed here.

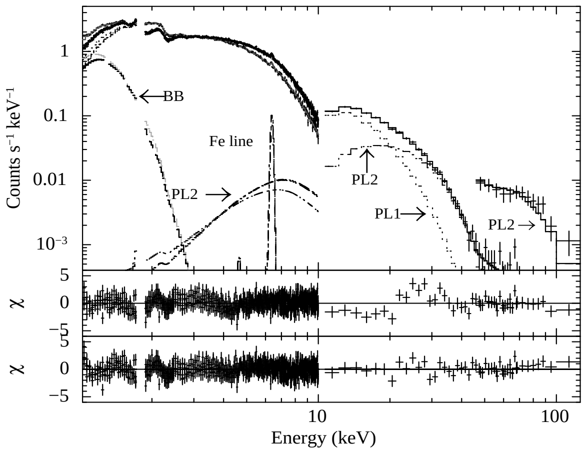

Figure 5. Energy spectrum of A0535+262 obtained with the XIS, PIN, and GSO detectors of the *Suzaku* observation, along with the best-fit model comprising a blackbody component (BB), an NPEX power-law continuum model, a narrow iron line emission (Fe line), and a cyclotron resonance factor at ~ 45 keV. The negative and positive power laws are marked by PL1 and PL2, respectively. The middle and bottom panels show the contributions of the residuals to χ^2 for each energy bin for the cutoff power-law continuum model and the NPEX continuum model, respectively.

4.1 Relation between spectral evolution and changes in the PDS

In transient accreting X-ray binary pulsars which show large variation in the rate of mass accretion during the X-ray outburst, it is found that the PDS break frequency follows the variations of the X-ray flux. This represents the changes of the magnetospheric radius with the mass accretion rate (Revnivstev et al. 2009). The increase in the mass accretion rate results in decreasing the size of the magnetosphere and hence the inner radius of the disk which brings the system away from the corotation, so that the characteristic frequency at the inner edge of the disk/flow increase. This has been verified by examining the PDS of transient X-ray binary pulsars such as A0535+262, 4U 0115+63, V0332+53, KS 1947+300 (Revnistev et al. 2009; Reig 2008). It was found in these systems that the break frequency in the PDS changes with the X-ray luminosity as $f_b \propto L_X^{3/7}$ which agrees with the standard theory of accretion onto magnetized compact objects.

Investigation of the timing and spectral variability of accreting Be/X-ray binary pulsars during major outbursts inferred that the transient Be binaries exhibit two branches in the colour-colour and colour-intensity diagrams. These are the horizontal branch corresponding to a low-intensity state showing the highest fractional rms, and the diagonal branch that corresponds to a high-intensity state during which the source stays for about 75% of the total duration of the outburst. Though the power density spectra of Be/X-ray binary pulsars are complex due to the peaks of the pulse period and its harmonics, the aperiodic variability can generally be described with low number of Lorentzian components (Reig 2008). Analyzing the colour-colour diagram and power density spectra of 4U 0115+63, KS 1947+300, EXO 2030+375 and V0332+53, it

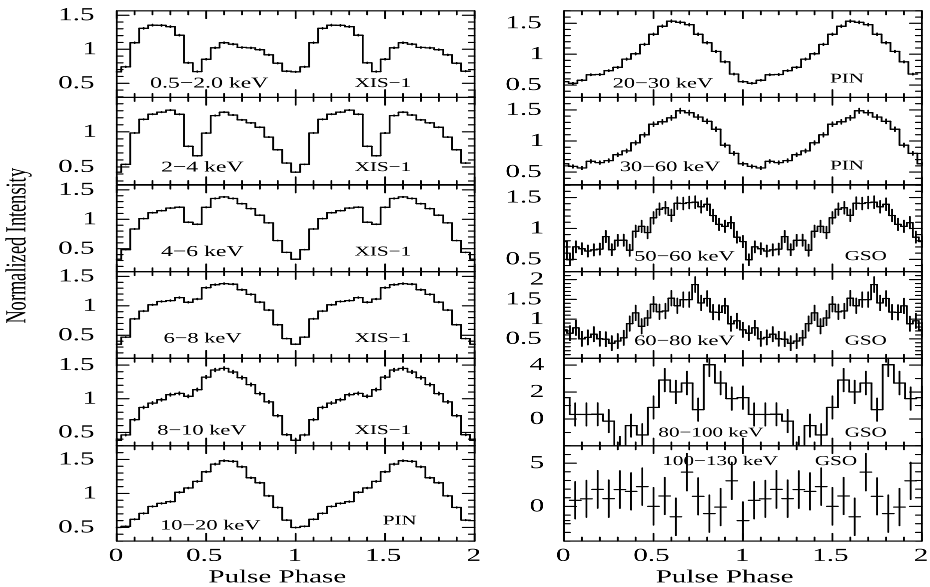

Figure 6. Energy resolved pulse profiles of GRO J1008-57. The presence/absence of the dip-like structure in the 0.35-0.45 pulse-phase range can be seen. The figure is taken from Naik et al. (2011a).

was found that the spectral-timing behaviour in Be/X-ray binaries shows the existence of spectral branches in the colour-colour and colour-intensity diagrams. At high and intermediate flux, the sources move along the diagonal branch; at very low count rate the soft colour decreases, while the hard colour remains fairly constant defining a horizontal branch. The low-intensity states are found to be more variable in terms of fractional rms.

4.2 Energy dependence of the pulse profiles

Luminosity and energy dependence of pulse profiles are seen in several transient HMXB pulsars. The pulse profiles of many transient sources show very strong energy dependence, often a multiple-peaked profile at soft X-ray energy bands ($\geq$ 8 keV) and a single-peaked or double-peaked smooth profile at hard X-rays (for example GRO J1008−57; Fig. 6; Naik et al. 2011a). Among some of the recent transients, the pulse profiles of GX 304−1 (Fig. 7), 1A 1118−61, and A0535+262 were found to be strongly energy dependent. Sometimes, the energy dependence also evolves during the outbursts. An interesting feature that appeared from the energy resolved pulse profiles of many pulsars is dip-like features in the pulse profiles. From pulse phase resolved spectroscopy, the dips are found to be due to a partial obscuration of the X-rays by matter that is phase locked to the neutron star.

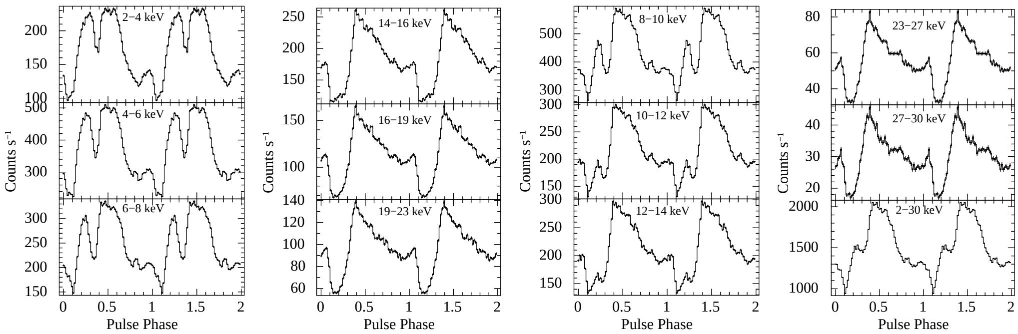

Figure 7. Energy dependent pulse profiles of GX 304-1 in different energy bands observed with *RXTE* during the peak phase of the outburst (2010 August 15− MJD 55423). The figure is taken from Devasia et al. (2011b).

4.3 Pulse phase resolved spectroscopy, dips and absorption in accretion stream

It has been found that the broad-band spectrum of transient HMXBs which show dip-like features in the pulse profiles, is well described by partial covering absorption model. There are cases where the phase averaged broad-band spectrum of pulsars was well described by several continuum models. However, a partial covering absorption model was found to be more suited over the power-law with high energy cut-off or NPEX model to fit the pulse-phase resolved spectra. As it is already described, in many cases, the power law with high energy cut-off, NPEX and/or partial covering absorption models were all statistically fitting well to the broad-band continuum spectra of transient pulsars such as GRO J1008−57 (Naik et al. 2011a), 1A 1118−61 (Devasia et al. 2011a; Maitra et al. 2011), GX 304−1 (Devasia et al. 2011b). While investigating the characteristics of the above pulsar at certain phases where dips or dip-like features were present in the energy dependent pulse profiles, pulse phase resolved spectroscopy showed that partial covering absorption model described the pulsar spectrum well at almost entire pulse phase ranges. Considering these results, the partial covering absorption model was preferred while interpreting the results from pulse averaged spectroscopy. Pulse phase resolved spectral analysis showed an increase in the value of absorption column density of the partial covering component and variation in the covering fraction during the dips or dip-like features in the pulse profile of the pulsars. The changes in the values of column density (N_{H2}) and the covering fraction during the dips in the pulse profiles naturally explain the energy dependence of the pulse profiles in transient HMXB pulsars. The changes in other spectral parameters such as iron emission line parameters, power law photon index are also seen in dip pulse phases compared to other pulse phases of the pulsars. A representative figure corresponding to the pulse phase resolved spectroscopy of transient HMXB pulsar GRO J1008−57 is shown in Fig. 8.

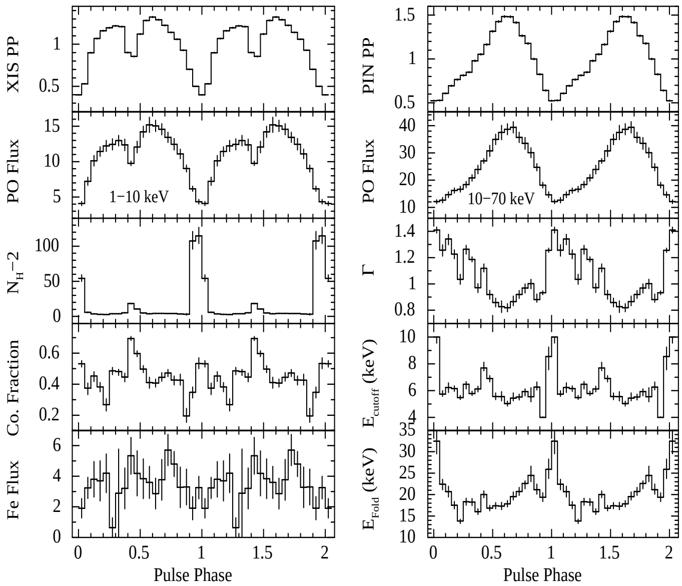

Figure 8. Spectral parameters obtained from the pulse-phase-resolved spectroscopy of *Suzaku* observation of GRO J1008−57. In the figure, the iron line flux (Fe Flux), power-law flux (PO Flux) and NH2 are plotted in the units of 10^{-12}, 10^{-10} erg cm^{-2} s^{-1} and 10^{22} atoms cm^{-2}, respectively. The XIS and PIN pulse profiles are shown in the top left-hand and top right-hand panels, respectively.

4.4 Pulse phase resolved measurements of the cyclotron lines

Pulse phase resolved spectroscopy of the CRSFs in X-ray binary pulsars can provide important information in understanding the combined effects of the accretion flow geometry, the physics inside the accretion mound and radiation transport in the highly magnetized plasma near the neutron star. To attempt phase resolved spectroscopy of CRSFs in X-ray pulsars, sufficiently long observations with detectors of excellent capability at hard X-rays are required. Pulse phase dependence of the CRSF is known in a few sources (e.g. Vela X-1: Kreykenbohm et al. 2002, 4U 1907+09: Rivers et al. 2010; GX 301−2: Heindl et al. 2004). Recently, pulse phase resolved spectroscopy of the CRSF in 1A 1118−61 was carried out using the *Suzaku* observation of this pulsar during its 2009 January outburst (Maitra et al. 2011). A remarkable dependence of cyclotron energy and depth with pulse phase has been found in 1A 1118−61. In this source, the cyclotron energy and depth show a variation of about 10 keV and by a factor 3, respectively, over the entire pulse phase. A pulse phase dependence of the CRSF is expected because of the simple fact that at different pulse phases the dipole geometry is being viewed at different angles. This has importance in understanding the emission pattern, both spectroscopic and geometric, from the accretion columns at the magnetic poles. However, some deep and sharp pulse phase dependent features in the CRSF may also imply a more complex underlying magnetic field structure.

5. Super Fast X-ray Transient (SFXT) phenomena, link between supergiant and Be XRBs?

A new class of HMXBs has emerged in the last several years, which consists of a compact star and a supergiant companion star. The remarkable feature of the SFXTs is their fast transient nature and several models have been proposed to explain this feature. Most of these binaries have wide orbits, very low X-ray luminosity during the quiescent period, and X-ray pulsations have been detected in few of these sources. One SFXT that stands out among all others is, IGR J16479−4514 (Jain, Paul & Dutta 2009a) with the smallest known orbital period of 3.32 d among the SFXTs and quiescent X-ray luminosity of $\sim 10^{34}$ erg s^{-1}, about two orders of magnitude brighter than the other SFXTs in quiescence. However, IGR J16479−4514 is much fainter than the persistent HMXBs with similar orbital period and is thus thought to be a link between the persistent HMXBs and the SFXTs while the SFXTs themselves are a link between the systems with supergiant companions and the Be X-ray binaries. Regarding the nature of the outbursts in the SFXTs, their duty cycle of the active period has been measured in several systems using extensive monitoring programs (Sidoli et al. 2008). There is evidence that the outbursts take place more frequently in certain orbital phases compared to the rest of the binary periods (Jain, Paul & Dutta 2009b) and this has implication for understanding of the SFXT mechanism.

5.1 Optical/IR results during transient X-ray outbursts

The optical companion of transient HMXB pulsars, specifically Be/X-ray pulsars are B-emission (Be) spectral-type stars and are characterized by high rotational velocities. These stars rotate at a speed close to critical limit so that the surface gravity mostly balances with the centrifugal force around the equator. The episodic equatorial mass loss in this type of stars forms a circumstellar envelope, called a Be disk, that orbits around the star. The Be stars show complicated line profiles containing an absorption component from the photosphere and an emission component from the circumstellar disk. The emission line profiles which reflect the nature of the circumstellar disk, show many kinds of variabilities on the time scales from days to several years viz. complete disappearance or truncation, evolution of the circumstellar disk, changes in line profiles – double peaked profiles etc. The change in line profiles in Be/X-ray binaries was explained due to the change in electron density in a region close to the Be star, triggered by uneven mass loss from the optical companion.

During X-ray outbursts in transient Be/X-ray binary systems, there are several occasions when extreme changes in line profiles of Be stars have been reported. The disappearance of the Hα emission line is generally used as a strong indicator for disk loss in Be stars. Corbet, Smale & Menzies (1986) found the Hα profile to change from a shell profile to an absorption profile over a period of four years in the Be/X-ray binary source 4U 1258-61 (GX 304-1). In case of Be/X-ray binary V635 Cas, it was observed that the Hα profile changed from emission to absorption during 1997 February – July (Negueruela et al. 2001). This was associated with a low photometric state in infrared magnitudes. The circumstellar disk formed again after the disk loss episode within a

period of about 6 months. Disk loss in another transient HMXB pulsar A0535+262 was inferred from a change in Hα emission profile to absorption during 1997 October – 1998 August (Haigh et al. 1999). It was also found that the hydrogen lines like Brγ in absorption on 1998 November, which is associated with disk loss event. The Hα line profile was found to show remarkable variability during the giant X-ray outburst of A0535+262 in 2009 November – December indicating the existence of a warped component (Moritani et al. 2011). During 2011 February – March X-ray outburst, a reduction in photometric JHK flux was also detected in A0535+262 binary system (Naik et al. 2011c). The disappearance of the circumstellar material in Be/X-ray binary X Per was evident from the conversion of Hα profile from emission to absorption (Norton et al. 1991). They also found that the near-infrared flux in JHK-bands was reduced, implying a common region of formation in circumstellar plasma for infrared continuum and Balmer line emission. In transient Be/X-ray binaries, the circumstellar disk loss phenomenon, related changes in the emission line features in optical and near-infrared spectra and the re-formation of the disk can occur over a period of a few days/weeks to months/years. Therefore, frequent monitoring of the optical companion in the HMXB system may detect several of such events during the transient X-ray outbursts which can lead to better understanding of the cause of such events.

5.2 Future with Astrosat

The first Indian space astronomy mission Astrosat, due for launch in 2012 will bring some qualitative changes in the study of some aspects of HMXB transients. Similar to *BeppoSAX* and *Suzaku*, it will provide a wide energy coverage. However, a much larger effective area of the LAXPC instrument (Paul 2009) in the 20–80 keV band compared to the earlier and current missions will enable very detailed studies of the cyclotron line features. In addition, Astrosat will also provide unprecedented simultaneous multi-wavelength observations, in three bands in the optical/UV region. This will enable some sensitive probe of the X-ray reprocessing in the surrounding medium, especially the accretion disk.

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